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14. ABSTRACT

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Army mobile ground communication systems typically require an antenna that provides large bandwidth, optimized power efficiency, and a small visual signature. A technique known as direct antenna modulation is a promising candidate to provide all three of these characteristics. By utilizing high-speed semiconductor switching components to directly modulate an antenna with a baseband pulse-modulated signal, the information bandwidth of the antenna may be decoupled from its resonant bandpass limitations. The direct modulation of an L-band microstrip patch antenna with fast-switching PIN diodes is described in this paper, as well as an introduction to the direct antenna modulation concept and a brief discussion of future research plans.

DIRECT MODULATION OF AN L-BAND MICROSTRIP PATCH ANTENNA USING INTEGRATED PIN DIODES

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Abstract: **Army mobile ground communication systems typically require an antenna that provides large bandwidth, optimized power efficiency, and a small visual signature. A technique known as direct antenna modulation is a promising candidate to provide all three of these characteristics. By utilizing high-speed semiconductor switching components to directly modulate an antenna with a baseband pulse-modulated signal, the information bandwidth of the antenna may be decoupled from its resonant bandpass limitations. The direct modulation of an L-band microstrip patch antenna with fast-switching PIN diodes is described in this paper, as well as an introduction to the direct antenna modulation concept and a brief discussion of future research plans.**

1. Introduction

When antenna structures are designed for Army ground communication systems, research efforts are typically focused on maximizing the information bandwidth and achieving high radiation efficiency with an antenna of the smallest physical size. Tradeoffs between these desired characteristics are often necessary during antenna design since antenna size and geometry generally control the resonant frequency, and since an antenna operating linearly at resonance with high radiation efficiency is intrinsically narrowband.

The standard rectangular patch antenna is an excellent example of a narrowband radiating element. The interactions between the energy that excites the patch at the feedpoint and the magnetic walls of the rectangular cavity geometry yield an input impedance that is highly frequency-dependent. This produces a resonant bandwidth that is dependent upon both the feedpoint impedance matching, represented in the following equation by the voltage standing wave ratio (VSWR), and the quality factor, Q_t, of the structure, [1]

$$BW = \frac{\Delta f}{f_0} = \frac{VSWR - 1}{Q_t \cdot \sqrt{VSWR}} \tag{1}$$

The quality factor of the patch is proportional to the summation of a wide variety of antenna losses, including radiation losses, Q_{rad}, conduction losses, Q_c, dielectric losses, Q_d, and surface wave losses, Q_{sw}, [1]

$$\frac{1}{Q_t} = \frac{1}{Q_{rad}} + \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_{sw}} \qquad (2)$$

Typically, Q_{rad} dominates the above expression for thin-substrate patch antennas while Q_{sw} dominates for thick-substrate structures. Since Q_{rad} is inversely proportional to power lost or radiated, and the power radiated is directly proportional to substrate thickness, then Q_{rad} is inversely proportional to substrate thickness. On the other hand, surface wave losses increase significantly if the substrate thickness is too large. [1] Thus, design compromises must be made regarding the substrate thickness to optimize both Q_{rad} and Q_{sw} and consequently optimize the antenna bandwidth and radiation efficiency. In this way, the bandwidth of the commonly-used patch antenna is significantly limited by both its resonant impedance feed matching and the losses associated with its quality factor components.

When traditional antenna modulation techniques are applied to a patch antenna in a communication system, the information bandwidth of the system will be significantly constrained by the bandpass nature of the antenna geometry. However, the system information bandwidth may be decoupled from the limits of the resonant antenna bandwidth by employing direct antenna modulation [2], a novel modulation technique that has only begun to be explored.

2. Background

Direct antenna modulation involves the incorporation of high-speed semiconductor switching technology with a radiating element in order to decouple the information bandwidth and radiation efficiency from the limiting bandpass nature of a resonant antenna and to eliminate the reliance of antenna size and geometry on the desired information signal frequency. By applying semiconductor switching techniques similar to those described in a US patent on synthesizer radiating systems [3] and those utilized for high-efficiency Class-D amplifiers [4], a unique antenna modulation system can be employed. A basic implementation of direct antenna modulation that is being employed in this research is shown in Figure 1.

After an antenna is designed and constructed to operate at a desired resonant frequency, one or more high-speed semiconductor switches, such as Schottky or PIN diodes, are connected between the antenna and the ground plane. An RF carrier wave at the resonant frequency of the patch antenna passes through a bias tee circuit and drives the antenna at

resonance through a feedpoint. Simultaneously, a lower-frequency baseband information signal, in digital pulse train format, passes through the bias tee circuit to the feedpoint and controls the diode switch. When the baseband signal has a value below that of the diode junction voltage, V_d, the switch displays high impedance to the carrier wave-generated oscillating charges on the patch antenna and the antenna efficiently radiates the carrier wave. When the baseband signal has a value close to or higher than that of V_d, the switch closes and provides a direct path for the oscillating charges on the patch antenna to flow to ground, causing antenna radiation to effectively cease. [2], [5] In this way, the digital baseband information signal is directly modulated onto the carrier wave. The antenna always radiates at or near its resonant frequency, producing high radiation efficiency. Also, the antenna geometry and size are no longer dependent upon the baseband information signal frequency, but are mainly dependent upon the desired carrier wave frequency. The information bandwidth of the system is also decoupled from the resonant bandwidth of the antenna and is mainly limited by the switching characteristics of the incorporated diode. This should result in a significant increase in the available information bandwidth, well beyond that which is provided by a linearly-operating resonant antenna that is inherently limited by its bandpass effect.
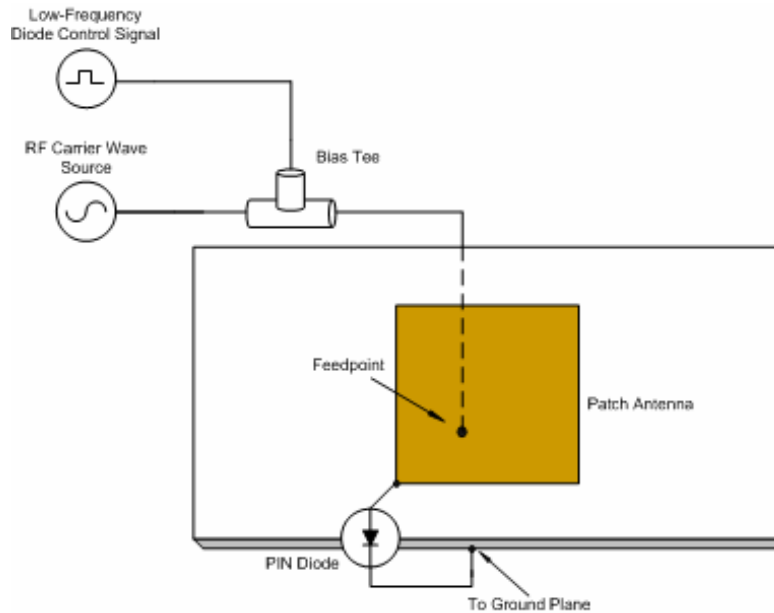

Figure 1. Basic implementation of direct antenna modulation.

Because 80% of the Army's mobile ground communications occurs below 1 GHz with dipole antennas that can be several meters in length [6], the reduction in visual signature resulting from the implementation of direct antenna modulation could be immense. With the incentive of compact antenna geometry and an increase in information bandwidth beyond that of a linearly-operating resonant antenna, further investigation of this promising antenna modulation technique is conducted and documented in this paper.

3. Analysis and Design

A symmetrical 1.5 GHz patch antenna was designed, simulated, and constructed to be the radiating element in the direct antenna modulation experiment. With a narrow resonant bandwidth of ~16 MHz for 15 dB or better return loss (VSWR = 1.43), there is significant room for improvement that direct antenna modulation may offer to the information bandwidth of the system. By driving the antenna at resonance and directly modulating it with an integrated high-speed diode switch being biased by an external pulse train, the frequency of this external modulating signal is predicted to far exceed the resonant bandwidth of the antenna and still produce a clear demodulated waveform at the receiving end of a communication system.

When direct antenna modulation is implemented with this patch antenna design, the diodes should be placed between the antenna and the ground plane at locations where the volume current density (and consequently the electric field) is at its highest value. This will maximize the switching effect of the integrated diodes and consequently yield the cleanest modulation effect. J_{vol} and E-field magnitude and vector plots from an HFSS [7] simulation of the symmetrical patch antenna were used to find these points.

A model of the microstrip patch antenna was constructed in HFSS, as shown in Figure 2. The copper ground plane on the bottom surface of the substrate was approximated as an infinite perfect electric conducting (PEC) ground plane, while the patch antenna above the substrate was approximated as an actual copper tape slab, with a thickness of 88 μm. The substrate was modeled after a 7.6 x 15.2 cm G-10 epoxy glass board with a thickness of 1/16" and relative dielectric constant of 4.24 at 1.5 GHz. The dimensions of the symmetric patch antenna model were set to 4.76 x 4.76 cm, with a feedpoint ~2.38 cm along the patch diagonal.
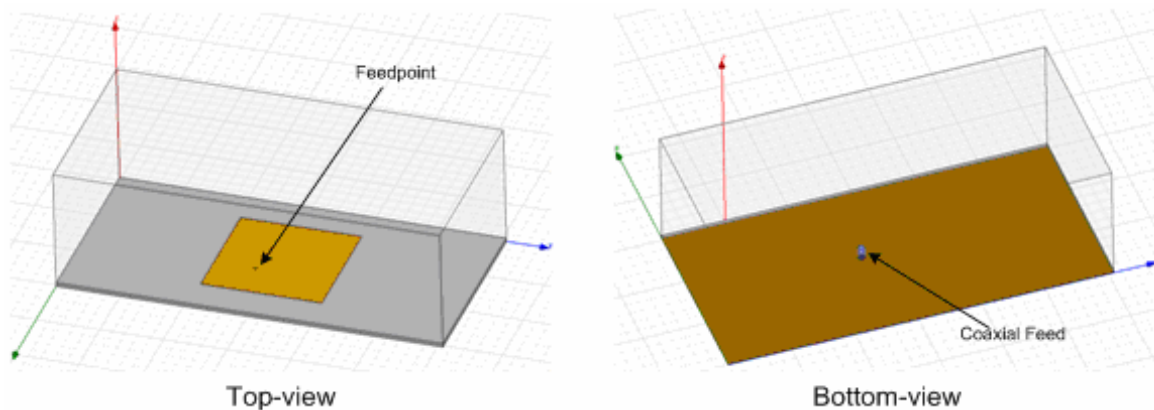

Figure 2. HFSS model of symmetric microstrip patch antenna.

The resulting J_{vol} magnitude and vector plots of this simulation are shown in Figure 3. The highest points of the volume current density appear to occur near two of the corners of the square patch, along the feedpoint diagonal. These points were confirmed by the E-

field plots (not shown in this paper). When diodes are integrated with the patch antenna in the direct antenna modulation experiment, they should be placed at or around these locations to maximize the diode switching effect.
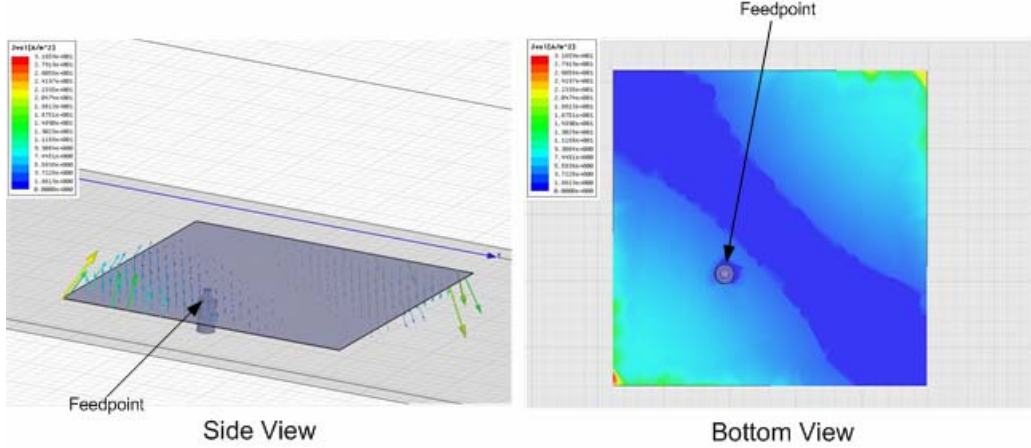

Figure 3. J_{vol} magnitude and vector overlay for HFSS simulation of patch antenna.

A number of semiconductor device characteristics must be considered when a Schottky or PIN diode is incorporated into a direct antenna modulation system as a switching element. The diode must be able to switch 'on' and 'off' fast enough to accommodate the baseband information signal that controls the diode bias. In previous direct antenna modulation research efforts, the switching "turn-off" period seemed to be significantly affected by the carrier lifetime of the semiconductor device. [2], [5] By using a diode with a very small carrier lifetime, the upper limit to the directly-modulated antenna's information bandwidth should be significantly increased.   Another important diode characteristic pertaining to direct antenna modulation is the junction capacitance. Since the diode must effectively function as an open circuit at 0 V bias, it is important to minimize its junction capacitance and consequently maximize its 0 V bias impedance value as a carrier wave passes across it.

For this direct antenna modulation experiment, the *Skyworks Solutions* SMP1340 PIN diode [8] was selected as the switching element. The carrier lifetime of the SMP1340 is specified as ~100ns, making it a suitable fast-switching device. The junction capacitance of this diode was also suitably low, being 0.3pF at 0 V bias. With a carrier wave frequency of 1.5 GHz passing across the diode, the resulting impedance is,

$$Z = \frac{1}{j\omega C} = \frac{1}{j \cdot 2\pi \cdot 1.5 \cdot 10^9 \cdot 0.3\,pF} = j354\,\Omega \tag{3}$$

Thus, at 0 V bias, the diode will still function as a "closed" switch – not quite a true open circuit but possessing a reasonably high impedance value to be deemed an effective open circuit.

4. Experiment

Two functional 1.5 GHz patch antennas were constructed according to the specifications detailed above to serve as the transmit/receive devices of a direct antenna modulation communication system. The experimental resonant frequency was measured as ~1.56 GHz. This difference between the designed and measured resonant frequencies is attributed to the difference in the initially assumed $\varepsilon_r = 4.8$ and the later measured $\varepsilon_r = 4.4$ dielectric constant of the G-10 epoxy glass substrate of the patch antenna. A microstrip bias tee circuit was then designed and fabricated to isolate the RF port and the baseband diode bias control signal port from one another and to provide a common output port to the transmit antenna's feedpoint. Finally, two *Skyworks Solutions* SMP1340 PIN diodes were soldered between the patch antenna and the ground plane of the G-10 epoxy glass board, as shown in Figure 4, to serve as the switching devices for the implementation of direct antenna modulation.
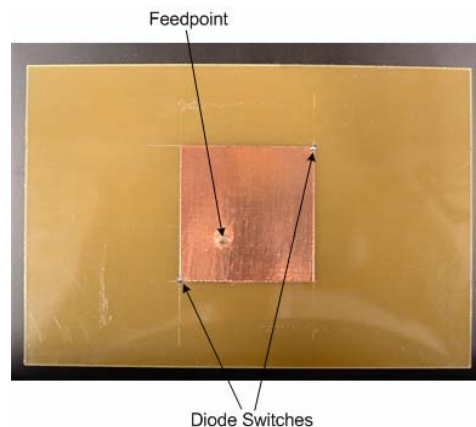

Figure 4. 1.56 GHz patch antenna with integrated PIN diodes.

With these components completed and fully integrated, the direct antenna modulation technique was then tested. A diode bias control signal with peak-to-peak voltage amplitude of ~0.8 V was produced by the *Wavetek* Model 145 function generator and sent into the low-frequency signal input port of the bias tee circuit, while a 1.56 GHz carrier wave was produced by the *Hewlett-Packard* 8614A signal generator and sent into the high-frequency signal input port. The 0.8 V amplitude for the diode bias control signal corresponded to the optimal SMP1340 forward bias voltage range of ~0.7 to 0.9 V. The frequency of this signal was varied from 100 kHz to the function generator limit of 20 MHz. The output port of the bias tee circuit was connected to the feedpoint of the transmit patch antenna and the feedpoint of the receive patch antenna was connected to

the *Tektronix* DSA 602A digitizing signal analyzer. This experimental setup is shown as a block diagram in Figure 5.
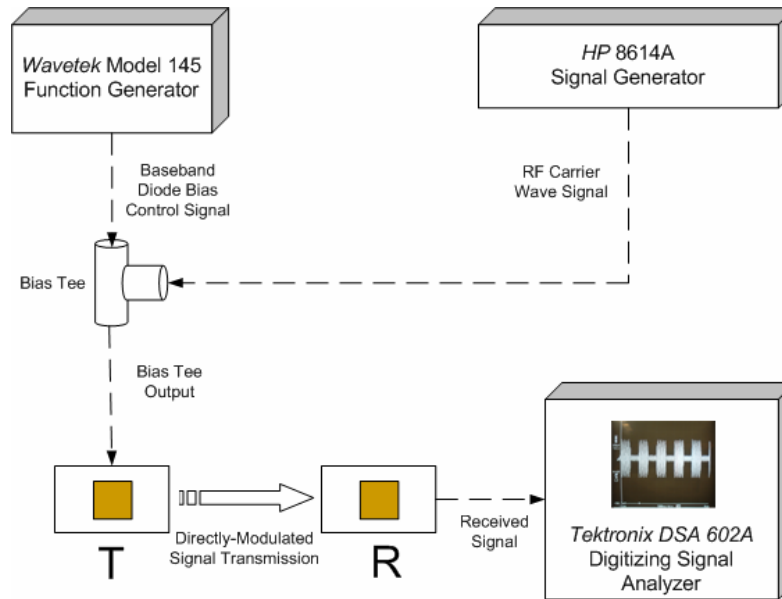

Figure 5. Block diagram of direct antenna modulation experiment.

The modulation effect of the baseband signal-controlled diode switch on the radiated 1.56 GHz carrier wave was examined by displaying the received carrier wave on the signal analyzer. The direct pulse modulation of the radiated carrier wave by the pulse-train biasing of the diode switches could clearly be seen, as shown in Figure 6. When the diode bias control signal had a value of 0 V (diode switch open), the carrier wave radiation was maximized and the received signal amplitude averaged ~40 mV. When the diode bias control signal had a value of ~0.8 V (diode switch closed, in forward bias), the carrier wave radiation was significantly reduced and the received signal amplitude averaged ~5 mV.
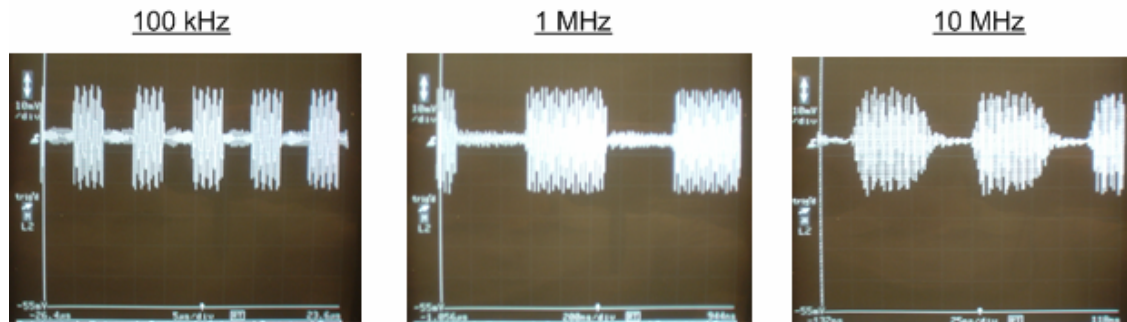

Figure 6. Directly-modulated carrier wave (viewed on signal analyzer).

For the majority of the 100 kHz – 20 MHz modulation frequency range that was tested, the pulse shape of the input diode bias control signal was well-preserved in the received directly-modulated carrier waveform. It should be noted that the received waveform did seem to become increasingly distorted in shape for frequencies between 10 MHz and 20 MHz, yet it still maintained a reasonably clear pulse shape.
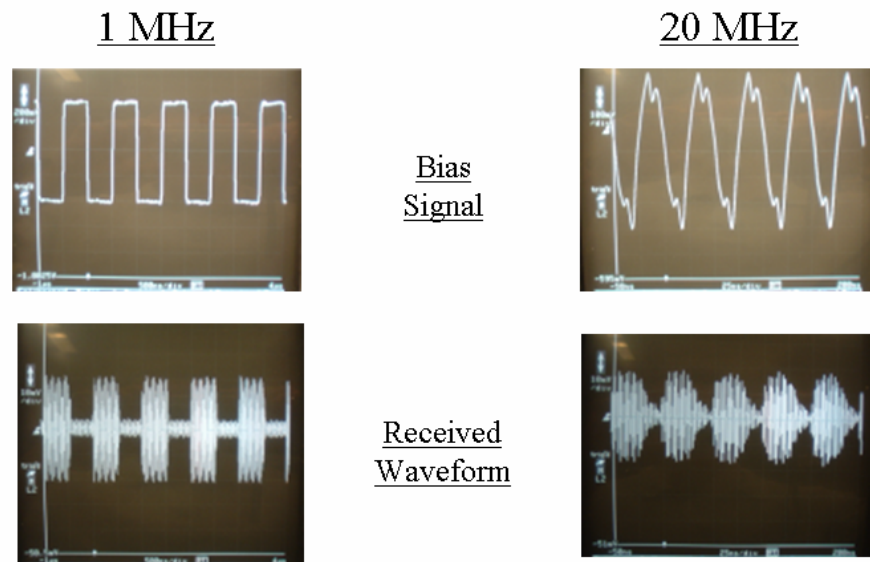

Figure 7. Effects of distorted function generator signal on modulated waveform.

This small distortion was most likely caused by the 20 MHz upper frequency limit of the function generator, as opposed to limitations related to the direct antenna modulation technique. A comparison of the function generator output and the received signal waveform is shown in Figure 7 and clearly supports this theory. With a function generator that can provide a clean 20+ MHz pulse train, the direct antenna modulation technique should produce a clean pulse-modulated carrier waveform for modulating frequencies well above the established narrowband antenna bandwidth.

5. Conclusion

The direct antenna modulation technique was successfully demonstrated by this experiment. The 20 MHz upper frequency limit on the available function generator restricted the extent to which the potential increase in system bandwidth could be explored. However, it was promising that the received pulse-modulated carrier waveform still retained a clear pulse shape (albeit the increasingly distorted pulses of the function generator output), even as the modulating signal frequency surpassed the resonant antenna bandwidth of ~16 MHz. Further experiments involving the direct antenna modulation technique are encouraged by these results and will be conducted in the near future. Such experiments will include a full investigation of the bandwidth

increase potential with a higher-frequency function generator and an examination of the bit error rate as the modulation frequency increases. The next step will be to explore ways to computationally model direct antenna modulation, which will allow for a deeper understanding of the underlying mechanisms of this technique and may spur improved methods of its implementation. The long-term goal of direct antenna modulation research is its application to Army communication systems, with a focus on increasing system bandwidth and reducing the visual signature of the Army's mobile ground communication system antennas.

6. Acknowledgements

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